Variability of Physical and Chemical Characteristics along the 70-m Isobath of the Southeastern Bering Sea

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Abstract

From observations of ice cover, temperature, salinity, currents and nitrate, it is evident that along-shelf variability was significant over the middle shelf of the eastern Bering Sea, but less distinct than the cross-shelf variability. Along the 70-m isobath, three zones were evident: the southeastern cold pool (~57°N); an intermediate zone, consisting of warmer water, with weaker stratification; and the northern cold pool, extending northward from 58°N. Small-scale (~20 km) horizontal features that persisted for months were common. Nutrient concentrations were related to salinity and were replenished more uniformly over the southern shelf, than north of the Pribilof Islands. Although mean currents were weak (~1 cm s^{-1}), short energetic advective events impacted the temperature and salinity structure.

1. Introduction

Cross-shelf variability over the Bering Sea shelf has been discussed extensively (e.g., Coachman, 1986; Schumacher and Stabeno, 1998; Stabeno et al., 1999) and three distinct shelf regimes (coastal, middle, and outer) have been identified. Each is distinct in hydrographic character, with the coastal domain well mixed or weakly stratified, the middle shelf two layered with the surface wind mixed layer abutting the tidally well-mixed bottom layer, and the outer shelf with well-mixed surface and bottom layers separated by a layer containing fine structure. In addition, variability along the inner front (~50 m isobath) of the southeast Bering Sea has been studied, revealing that the frontal structure along the Alaskan Peninsula is markedly different from that along the eastern coast of Alaska (Kachel et al., this volume). In contrast, the along-shelf variability has been mentioned only briefly (Whitledge and Walsh, 1986; Wyllie-Echeverria and Wooster, 1998).

On most shelves, the along-shelf variability is not as distinct as the cross-shelf variability. With a north-south orientation of the shelf and weak advection, a temperature gradient between the cooler northwest and warmer southeast is expected on the eastern Bering Sea shelf. Along shelf gradient in salinity is also expected due to the persistence of ice for longer periods over the northern portion of the shelf. These differences should persist in the lower layer of the middle, since it can be isolated from surface fluxes due to strong vertical stratification (Stabeno et al., 2001). The two-layer structure of the middle shelf results in a cooler lower-layer that persists through the summer. This lower layer is generally referred to as the cold pool (if temperature <2°C) or cool pool (if warmer than 2°C). Typically a cold pool exists to the north of 60°N, and in years of extensive ice coverage, a cold pool often can be found south of ~58°N (Wyllie-Echeverria and Wooster, 1998). While some evidence exists indicating that the southern cold pool is isolated from the northern cold pool, little is known about its persistence, year-to-year variability, or the mechanisms that cause its isolation. A more detailed understanding of how temperature and salinity vary is needed, as is an understanding of the mechanisms that define the spatial scales and patterns.

In this paper we explore the along-shelf variability along the 70-m isobath (the center of the middle shelf) using measurements from shipboard and moored instruments collected primarily during the last 5 years. Time series of temperature, salinity, and currents at two mooring locations (Sites 2 and 4; Fig. 1) are compared. In the next sections, the variability of temperature, salinity and nutrients along the conductivity-temperature-depth (CTD) transect following the 70-m isobath are discussed with respect to their seasonal, interannual and spatial patterns during the last few decades.

2. Data and Methods

Biophysical moorings were located at two sites along the 70-m isobath of the Bering Sea shelf. Data have been collected at Site 2, the southeastern site (Fig. 1), since 1995. Site 4 has been instrumented on three occasions (1996, 1999, and 2000), primarily during the spring and summer months. The winter moorings (October–April) at Site 2 and all moorings at Site 4 were taut-wire subsurface moorings instrumented to measure temperature, salinity, and fluorescence. In addition, if there was no nearby acoustic Doppler current profiler, current meters were incorporated into the mooring design. In general, temperature was measured every 3–4 meters in the upper 35 m and at 5–8 m intervals below that. During the summer at Site 2, a surface mooring was deployed that measured meteorological data in addition to instruments already mentioned. Details of the mooring design and instrumentation can be found in Stabeno et al. (1995, 2001).

The historical salinity data were collected using a variety of methods, including bottle samples, which were taken at 10 m intervals above 50 m and 20–25 m below. In the 1980s, data were collected using a variety of instruments measuring conductivity, temperature and depth. After 1993, CTD data were collected using a SeaBird 911-Plus with dual temperature and conductivity sensors as part of National Oceanographic and Atmospheric Administration (NOAA) and National Science Foundation (NSF) funded programs. These data were recorded on downcasts, which had descent rates of 15–30 m/min. Salinity calibrations were provided by water samples taken at most of the casts. These data indicate instrument accuracy better than 0.01 practical salinity units (psu). Data were routinely examined to remove spurious values. The dual sensors helped verify quality, and help ensure data recovery.

For the purpose of interseasonal and interannual comparisons at Sites 2 and 4, salinity and temperature profiles from historical data sets were identified. Stations selected for use at Site 2 were within 30 km in the along-shelf direction and 10 km across-shelf and had bottom depths between 70 and 76 m. At Site 4, casts used were within 30 km along-shelf and 20 km across-shelf and had bottom depths between 70 and 75 m.

Water samples were collected for analysis of nutrient concentrations at 0, 10, 20, 30, 50 m and near the bottom of each CTD cast. Nutrient samples were collected using polyethylene scintillation vials and caps, pre-washed with dilute HCL, and triple rinsed with sample water. Samples were stored upright in a refrigerator until they were processed, normally within 1–2 hours, using an onboard Apkem RFA Model 300 automated nutrient analyzer (Whitledge et al., 1981).

3. Mooring Sites 2 and 4

As mentioned, biophysical moorings were deployed at two sites along the 70m isobath. In September 1996, a subsurface mooring was deployed at Site 4 and recovered in 1998. The temperature recorder at 11 m failed, so data were only collected below 16 m. A comparison of this data set with those collected from a series of moorings at Site 2 (Stabeno et al., 2001), show a similar evolution of water column structure (Fig. 2). A two-layer system existed in September at both sites. By late October, the water column had become well mixed due to atmospheric cooling and wind mixing. Ice arrived over Site 4 (indicated by black) approximately a month earlier than at Site 2 and persisted several days longer. At both sites, once the ice was advected away (or melted) the water column quickly warmed by ~1°C, likely as a result of advection of warmer more saline water into the site by geostrophic currents. During June–August, the temperature in the bottom layer (below 30 m) was similar at both sites, but mixing events (seen in blue in the lower panel of Fig. 2) appear to extend deeper at Site 4 than at Site 2.

An examination of the depth-averaged temperature at both sites (Fig. 3a) reveals that during the last three decades Site 4 was, on average, cooler than Site 2. This is not unexpected, since Site 4 is farther north, which typically results in both slightly less solar heating, and the persistence of ice later into the year than at Site 2. During 1999 and 2000, data were collected at each mooring site with sufficient vertical resolution to calculate vertically averaged temperature (the data from 1996 mooring could not be used because of the lack of an instrument in the upper 20 m). Surprisingly, time series of the depth-averaged temperature during spring and summer show that during both these years Site 4 was warmer than Site 2 (Fig. 3b). This is also evident in the contours of temperature time series at the two sites (Fig. 4), where in April the water temperature at Site 2 was colder than at Site 4. Only at Site 2 is there evidence (black in early May 1999) of ice over the moorings. During both 1999 and 2000, the two-layer system formed in May at each site. In May through July of both years, the surface temperature at Site 2 was warmer, as a result of a shallower mixed layer in 1999 and greater warming in 2000 (Fig. 3b). The reverse was true in August 2000, when a shallower mixed layer at Site 4 resulted in sea surface temperature (SST) being warmer there. The lower layers warmed by a 2–3°C each year.

A defining characteristic of the Bering Sea shelf is sea ice (Stabeno et al., 2001). During summer the eastern Bering Sea shelf is ice free. Beginning in October, ice usually begins to form in polynyas and is advected southward by prevailing winds. It melts, freshening the water column and reducing the temperature of the water. In cold years, much of the eastern shelf can be covered in ice. During warmer winters, ice does not extend farther south than ~58°N (Stabeno et al., 2001). Since 1997, maximum ice extent has been similar (Fig. 5a) extending at least to 56°N, but the timing of maximum ice extent differed greatly among years. One way of looking at this temporal variability of ice coverage is to calculate the percentage of ice in a 1° band of latitude. Here we use the band 57°N–58°N; Site 4 is within the band and Site 2 just to the south (Fig. 5a). The maximum ice cover occurred in January 2000, but this ice was forced northward in early February by winds out of the south and melted (Fig. 5b). By mid February 2000 the band was largely ice free and remained so for the remainder of the winter and spring. In contrast, ice coverage over the southern shelf was less extensive in 1999, but significant ice persisted in the eastern part of the band until May. This persistence of ice at site resulted in colder water temperatures in late spring and summer 1999 than in 2000 (Fig. 3 and 4).

As evident in Figs. 2 and 4, ice is critical in setting up the initial conditions in the spring, and therefore plays an important role in the timing of the spring phytoplankton bloom (Stabeno et al., 2001; Hunt et al., this volume; Stabeno and Hunt, this volume). The salinity of the water is a function of the amount of ice melting and the timing of its retreat. An examination of the depth-averaged salinity from hydrographic casts near each of the mooring sites shows a marked difference in character between the two sites (Fig. 6). While at Site 2, the variability during late winter, spring, and early summer is high, by late summer or early fall the salinity appears to stabilize at ~31.7 psu. This pattern is also evident in the time series data from the mooring at Site 2 (Fig. 7). During years when there was a large amount of ice over the shelf during late winter and early spring (1995, 1997, and 1999), there was considerable freshening near the surface. In September or October, the variability is reduced and by late fall the water column is well mixed and salinity is ~31.7 psu. The only nearby source of higher salinity water is the shelf break. It has long been speculated that during fall and winter cross-shelf advection introduces slope water onto the shelf. These data sets support that hypothesis.

The tendency of salinity to return to a steady value by fall has important implications for understanding nutrient supply. Just as ice melt reduces the salinity of the water column, phytoplankton blooms consume nutrients. Each year approximately half of the nutrients on the shelf are utilized by biological activity and must be reintroduced from the nutrient supply at the slope (Whitledge et al., 1986). Salinity and nutrients are related, with higher salinity associated with higher nutrients. Primary production with its consumption of nutrients, can reduce the correlation between nutrients and salinity. During late fall and winter, and below the euphotic zone in spring and summer, there is a positive correlation between nutrients and salinity, although with a large amount of variance. The stability of the salinity during fall for the last three decades supports the idea that the replenishment of nutrients has been consistent over the years. From direct measurements, the maximum concentration of nutrient at Site 2 have been relatively constant for the last 5 years (Rho et al., this volume), with nitrate concentrations returning to ~15 μmole l^{-1} before the spring bloom.   Limited salinity data from Site 4, however, show much greater variability, and do not support the conclusion that salinity returns to a near constant value each fall. Likewise, nitrate concentrations appear to be more variable at that site.

4. CTD Transects

Contours of temperature along the 70-m isobath in September show a well-established two-layer system (Fig. 8). Surface temperatures are marginally warmer at the southeastern edge and cooler at the northwestern edge of the transect, and values were similar in each year. The lower layer, however, shows more horizontal structure. The southeastern cold pool (1999) or cool pool (1998 and 2000) is evident as an isolated area of cooler water, with the coldest temperatures located at the CTD station found at either the 210 or 270 km mark.   The differences in bottom temperature between years resulted from the previous winter’s ice extent and the timing of retreat. Ice retreated early (before March) in 1998 and 2000, and persisted into May in 1999 (Fig. 6). So there was time for temperatures to be modified by horizontal processes (mixing and advection) during spring 1998 and 2000, before the set up of the two-layered system.

An examination of transects of salinity along the 70-m isobath reveals a significant amount of small-scale horizontal variability. In 1998, an area of high salinity was observed at the CTD station located at the ~100 km mark, which surprisingly, persisted for a month (Fig. 9, top two panels). In May 1999, an area of high salinity was evident in the lower layer at Site 4, and an area of low salinity at the CTD station located at the ~200 km mark. The low salinity coincided with the cold pool (Figs. 8, middle panel), and resulted from ice melt. Remarkably, these features persisted for at least 4 months. In 2000, both the May and September sections lacked the smaller scale variability in salinity evident in the earlier two years (Fig. 9 bottom two panels), although the locations of minimum and maximum salinity follow a pattern similar to that observed in 1999. Possible mechanisms that could maintain such features are limited. The shelf in the region is very flat, with no sharp bathymetric features. The presence of eddies have rarely been observed over the middle shelf, but this is the most likely explanation for the observed persistence of features (Reed, 1998).

Nutrient samples were collected at each CTD station are shown in Fig. 10. As already noted, high nutrient concentrations are associated with higher salinity. For instance, the high nitrate concentrations (>21 μmoles l^{-1}) coincided with salinity above 32.4 psu in May 1999, and nitrate concentrations above 15 μmoles l^{-1} coincided with salinity >32.2 in April 1998. September (1999 and 2000) transects both show a depletion of nutrients in the upper layer, with higher nutrients found at the northwestern part of the transect. Interestingly, an increase in nutrients occurred in the lower layer at Site 4 between May and September 2000. In general, maximum nitrate values at Site 4 were highly variable, ranging from 12 μmoles l^{-1} (1998) to >21 μmoles l^{-1} (1999). This supports nutrient inferences of higher variability at Site 4 drawn from salinity distributions.

Currents at the two sites were highly variable in direction and magnitude, with the variance at Site 4 approximately 50% higher than at Site 2 (Fig. 11). The middle of the Bering Sea shelf is flat with few topographic features, and the currents do not parallel the distant coast. The mean currents over a period of a year are weak, but during shorter periods of days to weeks currents velocities can be substantial (Stabeno et al., 2001). Many of the decreases in temperature at Site 4 (Fig. 3) were related to southward flow. For instance, the sharp decrease in September 1999 was correlated with a pulse of flow toward the south. Similarly, the lack of increase in temperature in late June 2000 was associated with a period of relatively weak southward flow. Sudden changes in average temperature at Site 2 were less common. In general, Site 4 was impacted by advection to greater extent than was Site 2. A weak eastward flow has been observed in satellite-tracked drifter trajectories (Reed and Stabeno, 1996), just south of Site 4, and likely contributes to the formation of the intermediate zone separating the two cold pools.

5. Discussion

Just as three cross-shelf domains have been identified across the shelf in the southeastern Bering Sea, the variations in along-shelf hydrography of the middle shelf define three regions. These are: the southeastern cold pool, just northwest of Site 2; an intermediate zone, consisting of slightly warmer water; and the northern cold pool, extending northwestward from Site 4. The distributions of salinity and nutrients (nitrate concentrations) were well correlated on each of the 340 km transects. Warmer temperature and lower salinities of the surface layer coincide with nearly depleted nitrate levels. Colder temperatures and higher salinity waters were associated with higher concentrations of nutrients. The highest concentrations of nutrients were found in the vicinity of Site 4 during the spring.

The compilation of historical hydrographic data indicates that the mean salinity at Site 2 returns to a value of ~31.7 psu during September to November. This has held true for over 30 years of observations. This stability implies that there is a uniform source of salinity and nutrients to the area near Site 2, which is persistent and relatively well mixed. At Site 4, we observed much greater ranges of both salinity and nitrate, an indication of greater variability in source or magnitude of replenishment than at Site 2. Prior to August, the mean temperature at Sites 4 was warmer in both 1999 and 2000 than at Site 2, but long-term hydrographic data revealed these years to be anomalous. During no other year with data at both sites was the mean temperature at Site 4 greater than at Site 2. Small perturbations in the location of the southeastern cold pool and the transition zone can account for this. While the general characteristics of hydrography and currents along the 70-m isobath in the eastern Bering Sea are similar, results at biophysical moorings are somewhat sensitive to their exact positioning.

During each occupation of the 70-m transect small-scaled features (50–100 km wide) were observed and in two of the three years these features persisted for several months. The physical mechanism by which maintains them is unknown, but the most likely source is eddies. Some of these features were also observed in nutrient measurements such as ammonium. High concentrations of ammonium have been observed to persist for similar periods (Whitledge and Walsh, 1986; Whitledge and Luchin, 1999). A careful three-dimensional survey of such a mesoscale feature is necessary to understand the mechanisms and dynamics of how they can persist on a shallow shelf.

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Figure Captions

Fig. 1. Map of the study area. The filled circles indicate the CTD stations along the 70-m isobath. Sites 2 and 4 are indicated by open squares.

Fig. 2. Contours of temperature at Site 2 (top panel) and Site 4 (bottom panel) for 1996–1997. The areas of black indicate temperatures of approximately –1.7°C, which occur when ice is over the mooring site.

Fig. 3. Depth averaged (0–72 m) temperature at Sites 2 and 4: (a) Historical data from hydrographic casts in the vicinity of the moorings. (b) Time series of the depth averaged temperature using the data collected at the moorings for 1999 and 2000.

Fig. 4. Contours of temperature at Sites 2 and 4 for 1999 and for 2000 measured at moorings using SeaBird SeaCats and temperature recorders.

Fig. 5. Depth averaged (0–72 m) salinity at (a) Site 2 and (b) Site 4 from historical hydrographic casts.

Fig. 6. Maximum ice extent during each of the last 4 years (upper panel). The percentage of ice cover in the 1° band of latitude (57°N–58°N). Position of the ice edge and the percent of ice coverage was obtained from the weekly Alaska Regional Ice Charts which are produced by the Anchorage Forecast Office of the National Weather Service.

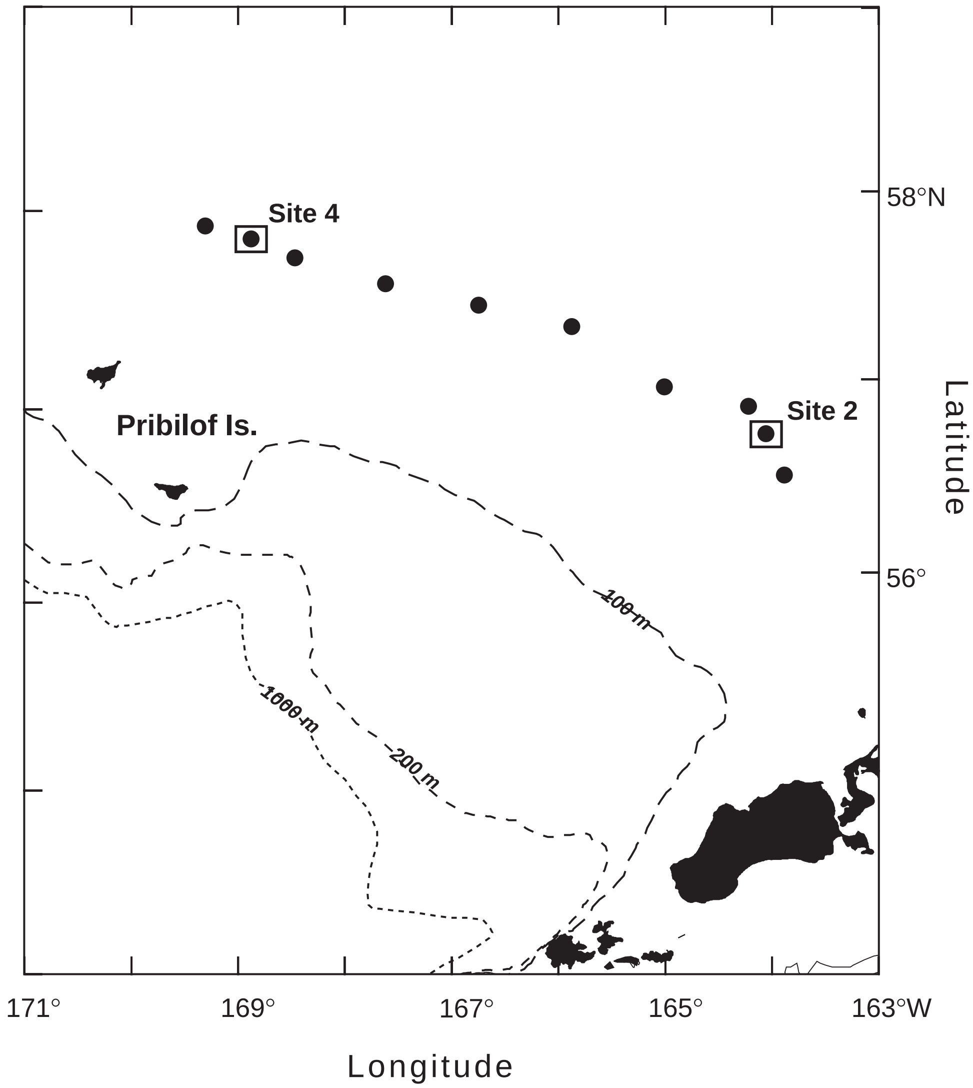
Fig. 7. Time series of salinity measured at Site 2. Typically there were instruments in the upper layer (0–15 m), and near bottom (~60 m), both of which are indicated in green. Salinity measured at intermediate depths is indicated by blue.

Fig. 8. Contours of temperature measured at the CTD stations along the 70-m isobath shown in Fig. 1. Distance is measured from north to south. Positions of casts are indicated by arrows at the bottom of each plot and positions of the moorings at labels M2 (Site 2) and M4 (Site 4).

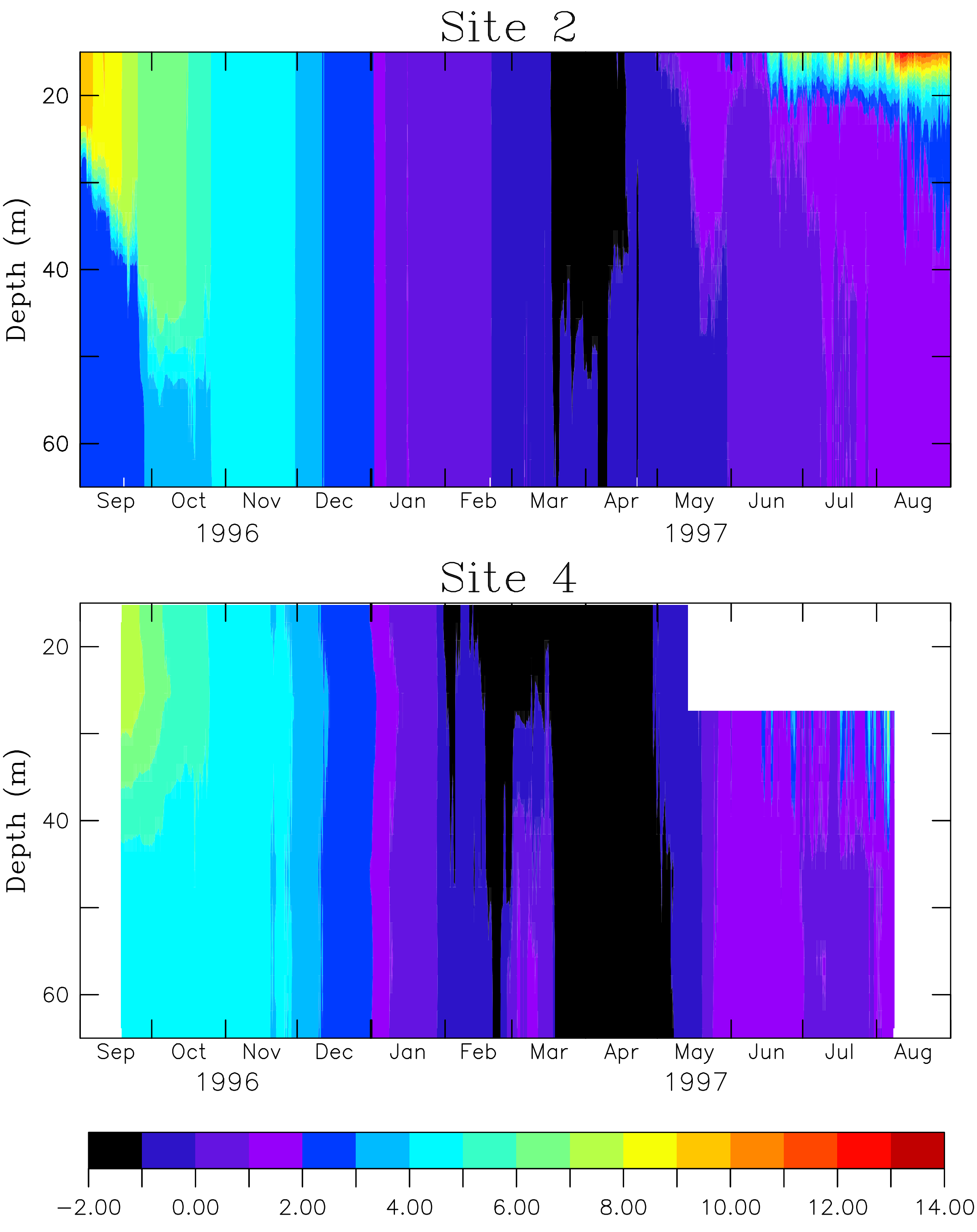
Fig. 9. Contours of salinity at CTD stations indicated on Fig. 1. Positions of casts are indicated by arrows at the bottom of each plot.

Fig. 10. Contours of nitrate (μmoles l^{-1}) measured at the CTD stations.

Fig. 11. Daily vectors of low-pass filtered currents measured at the two mooring sites. North is upward.



Stabeno: 70-m isobath -- Fig. 1



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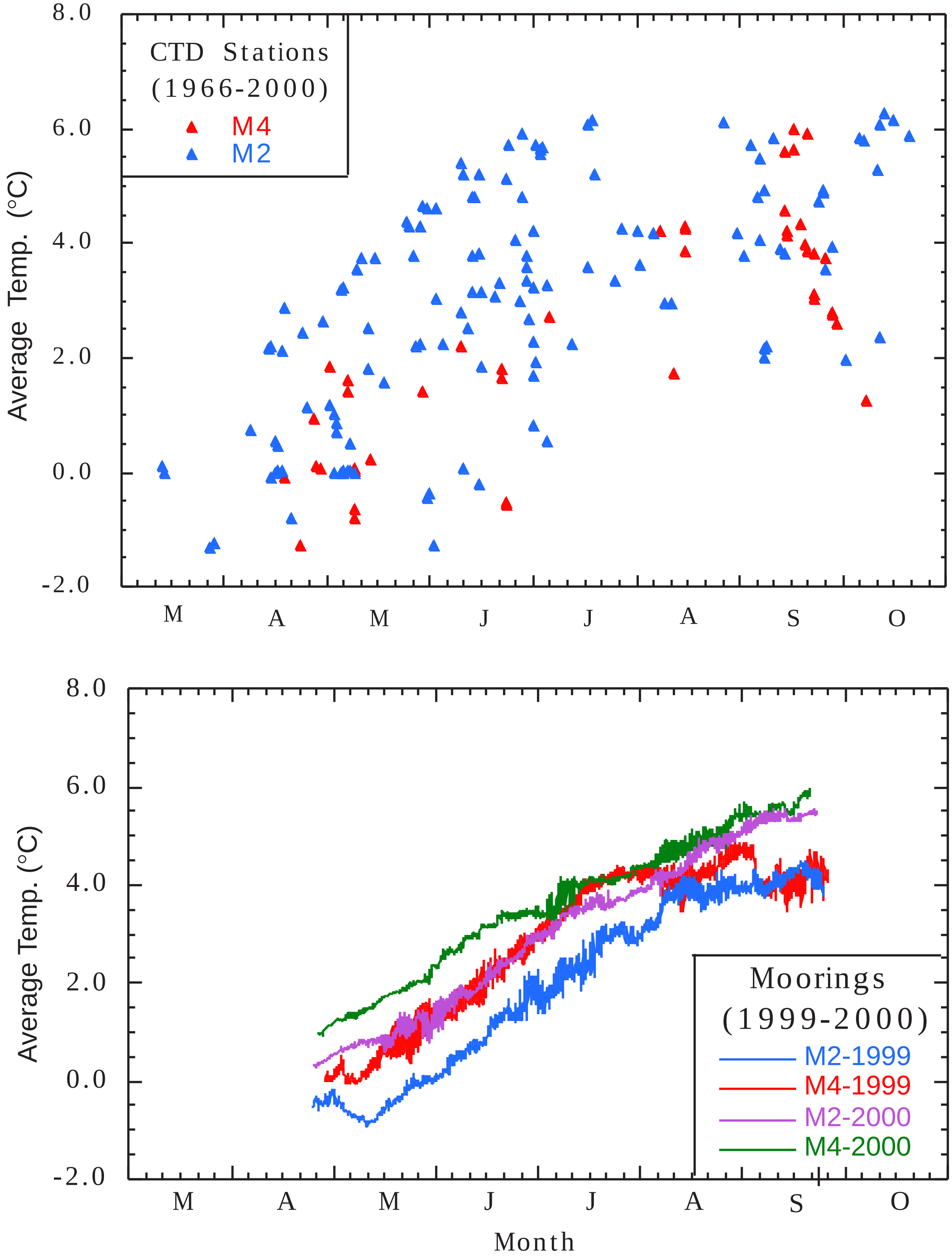

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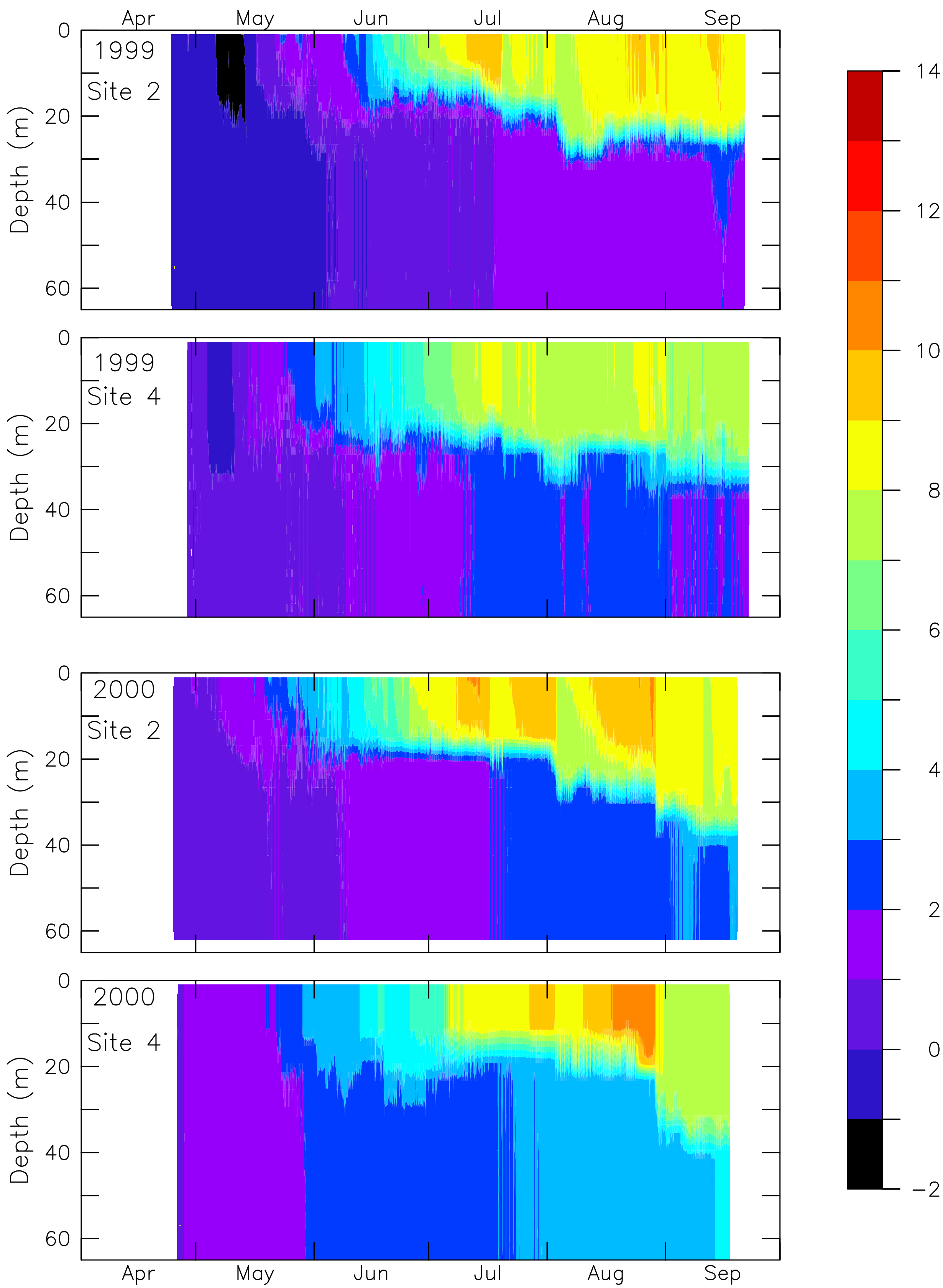

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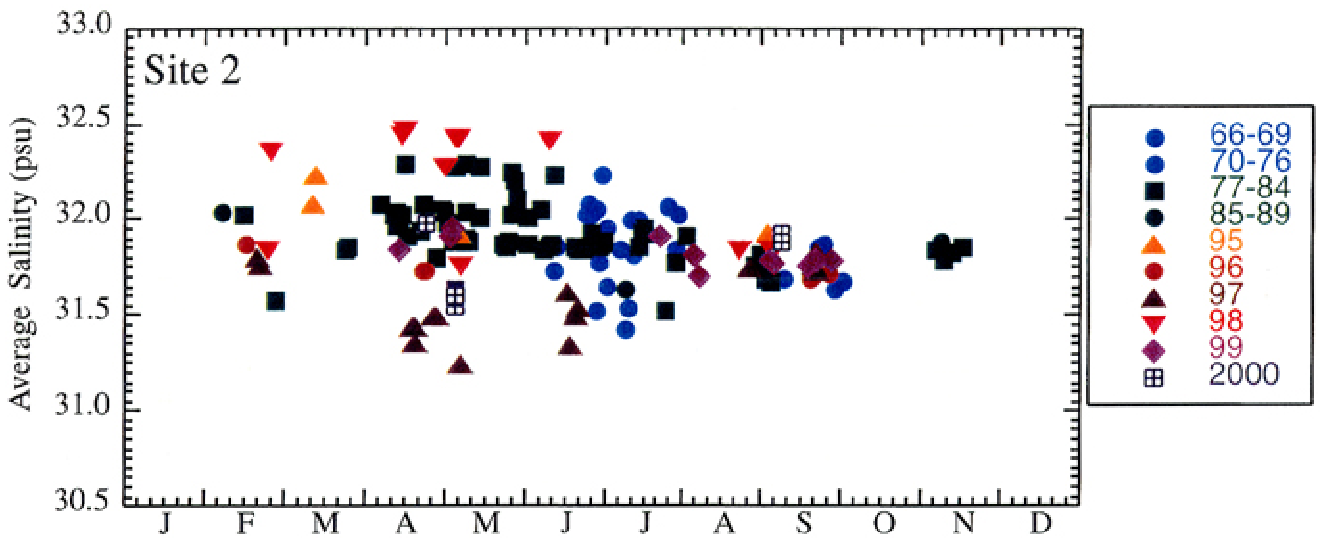

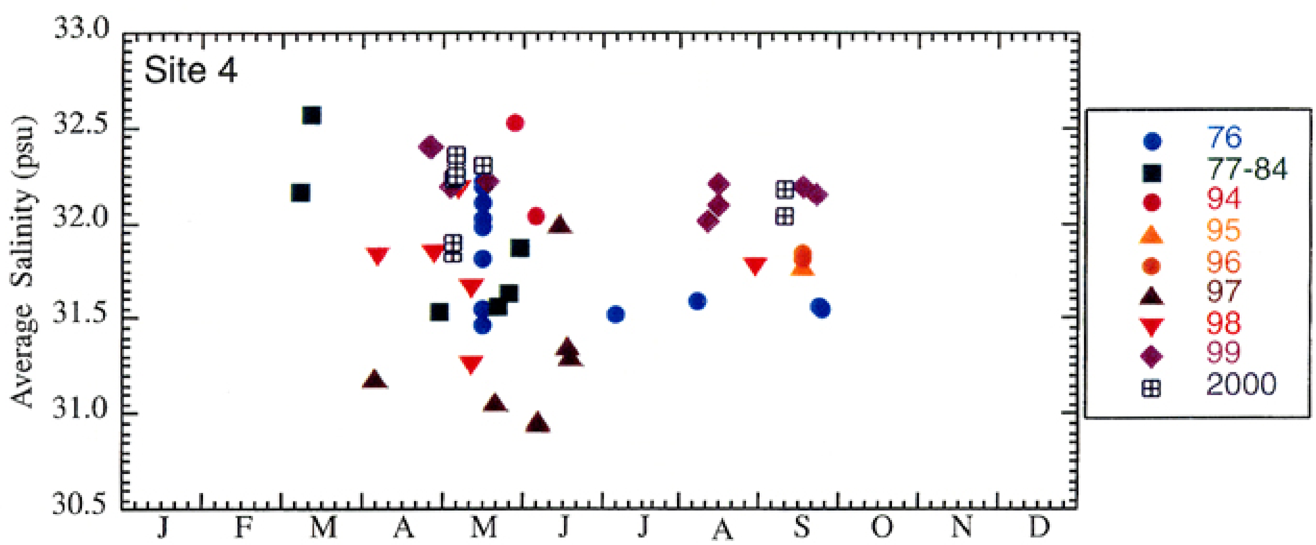

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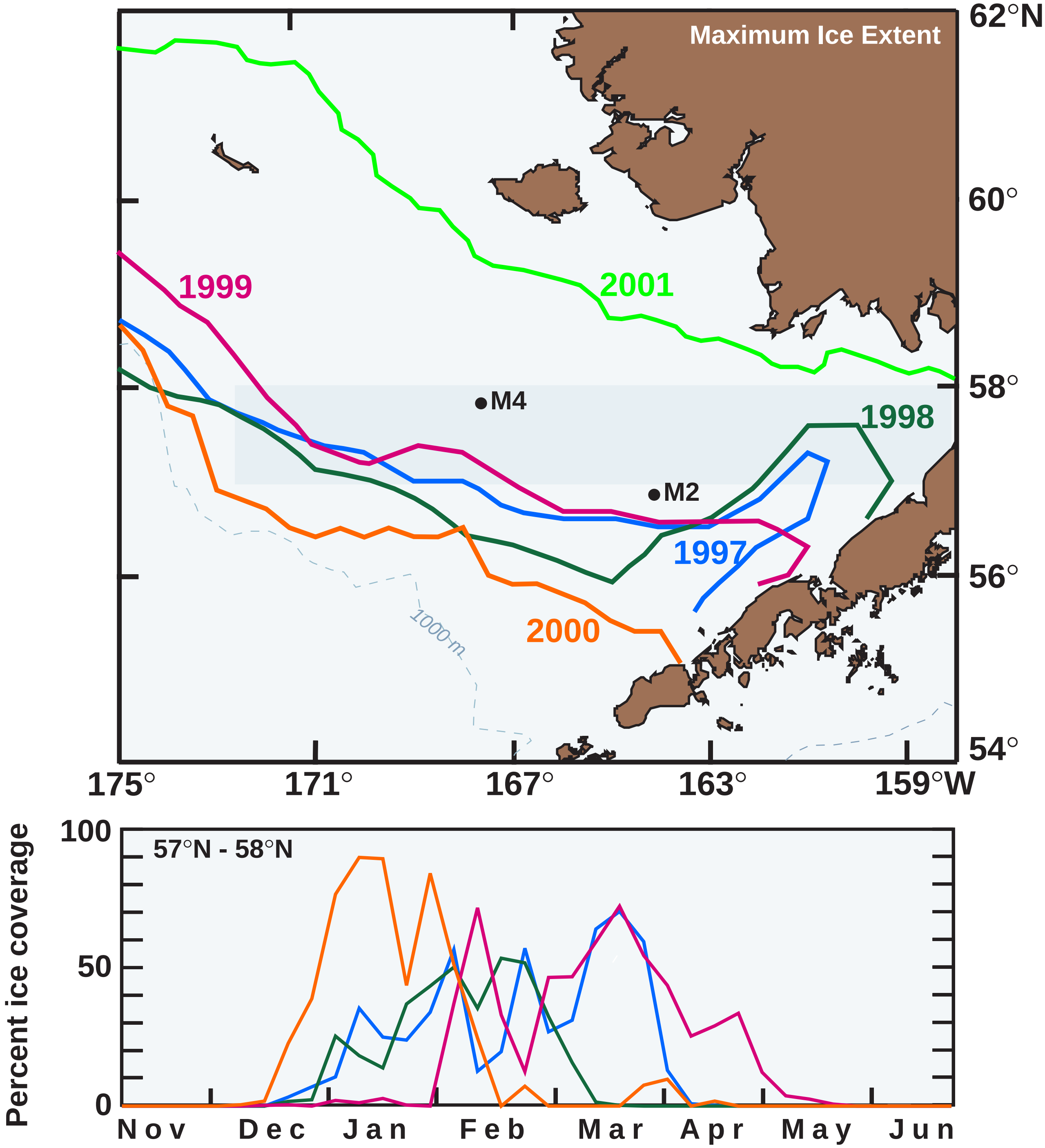

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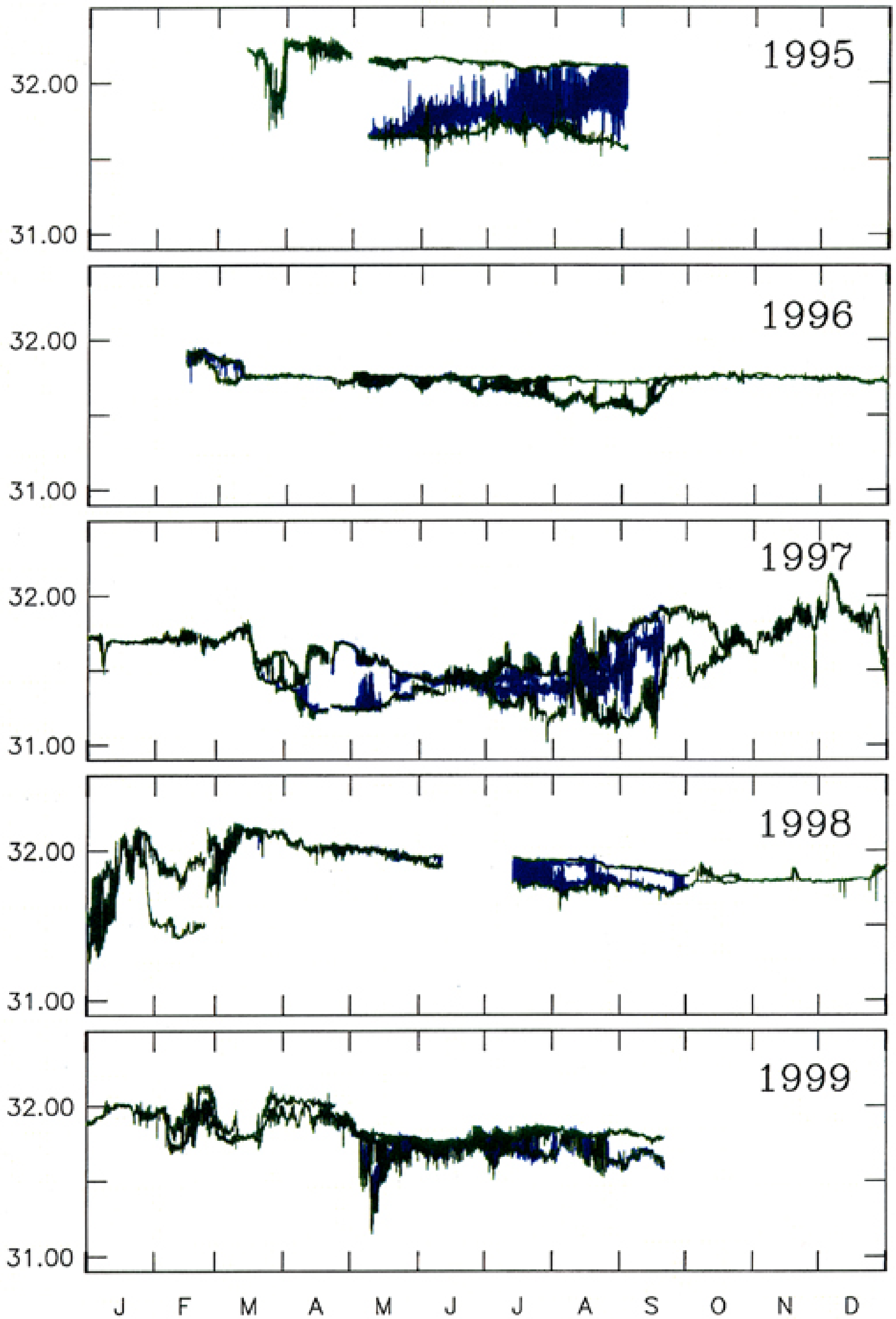

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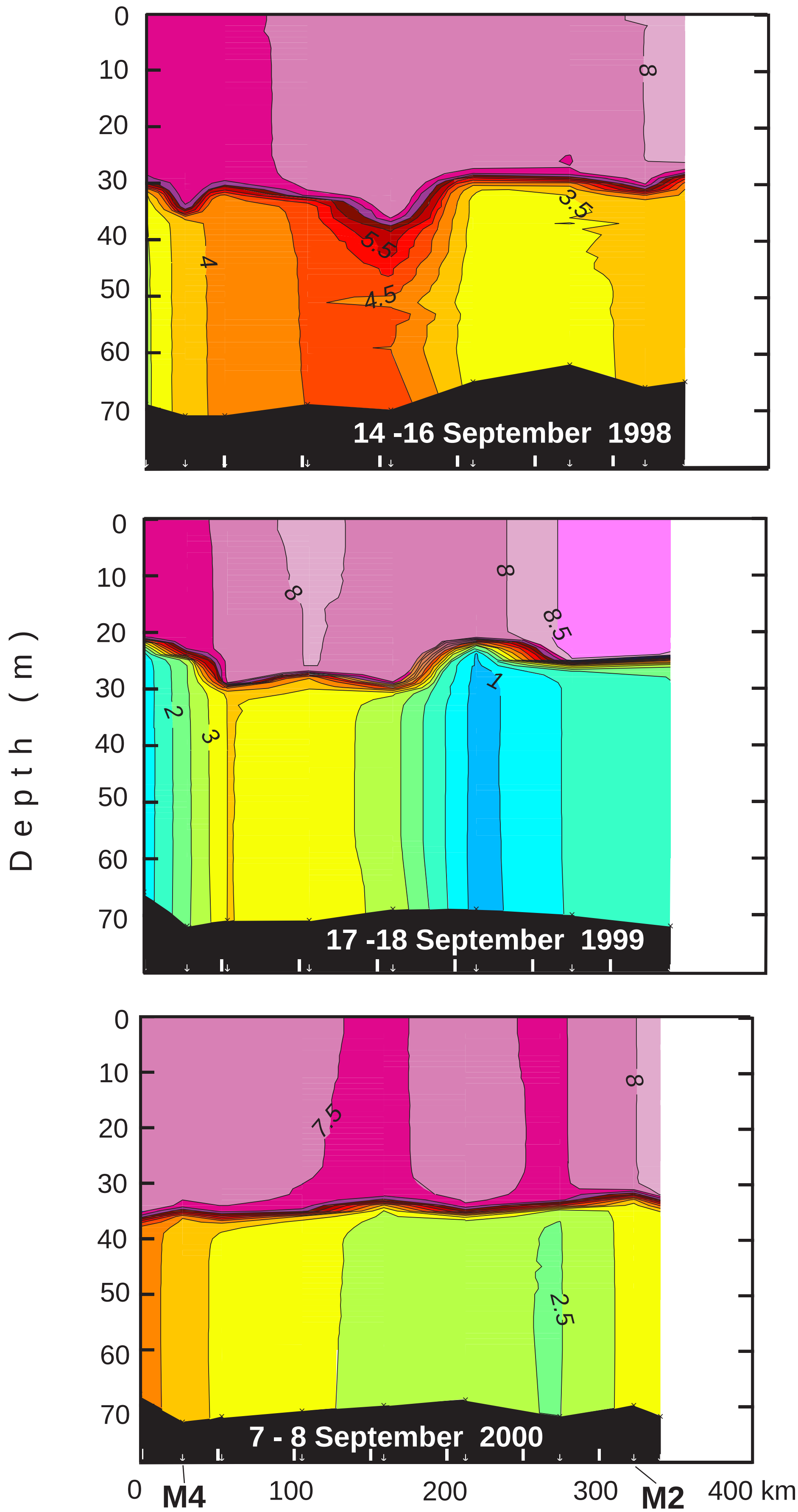

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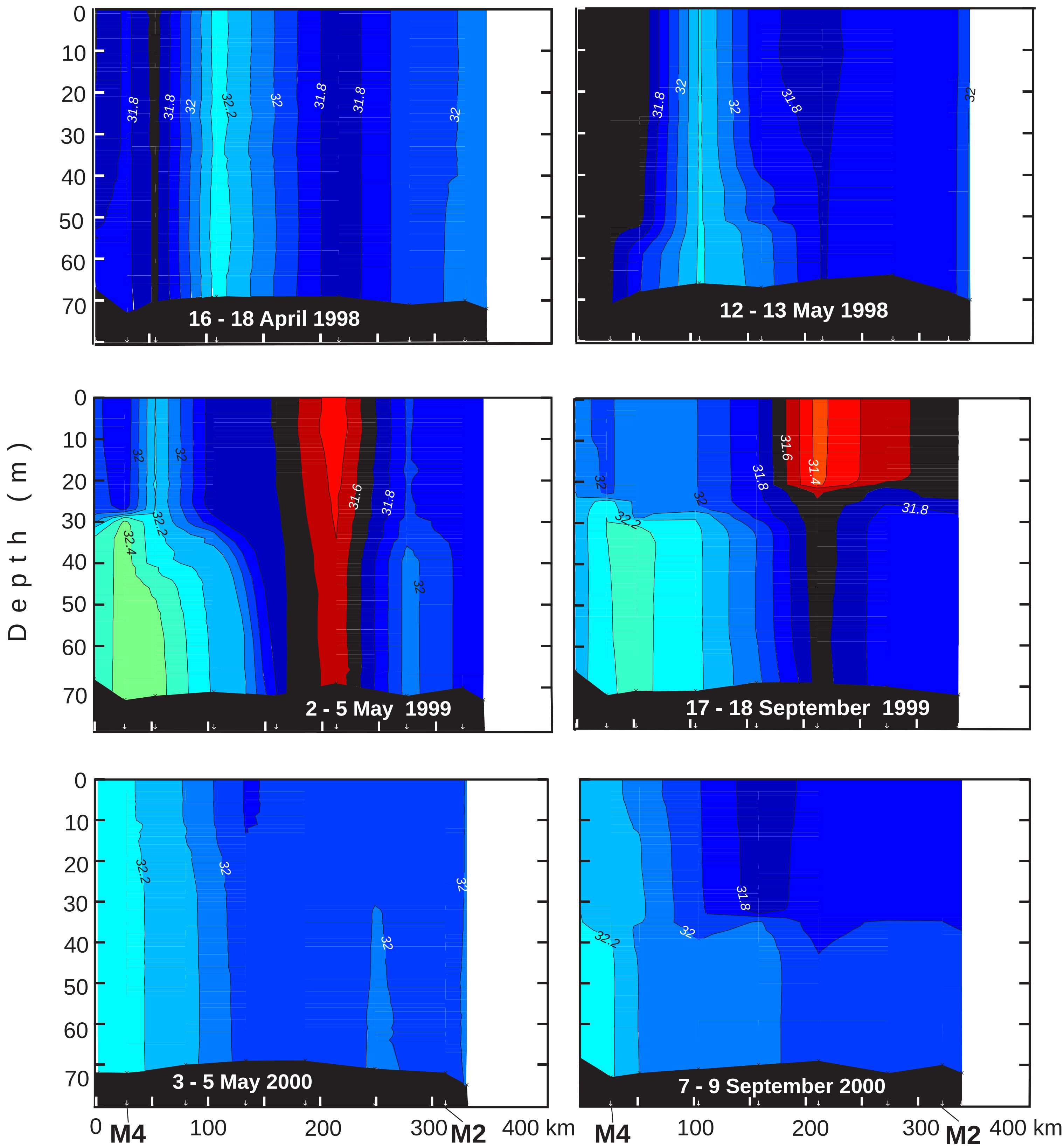

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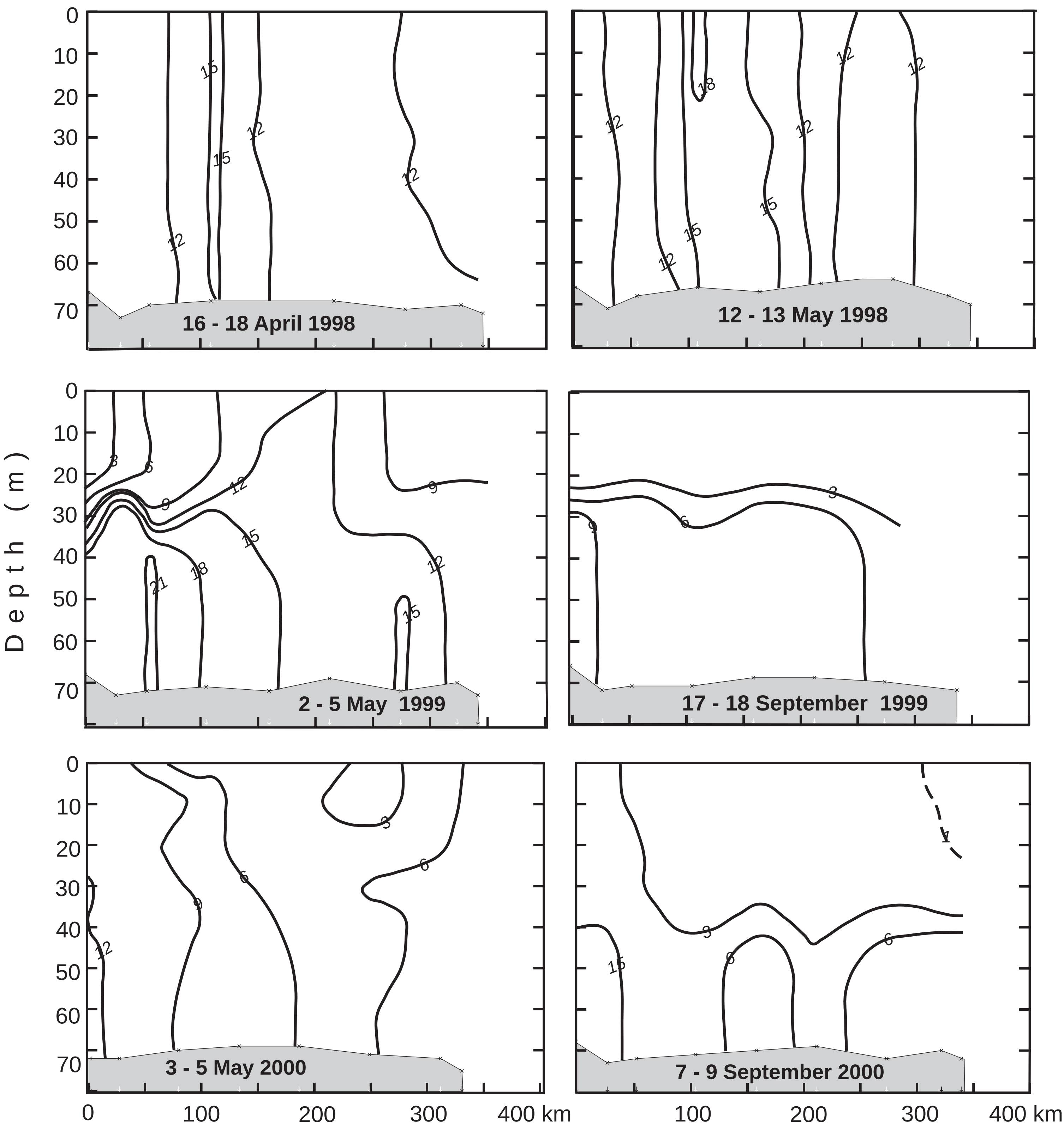
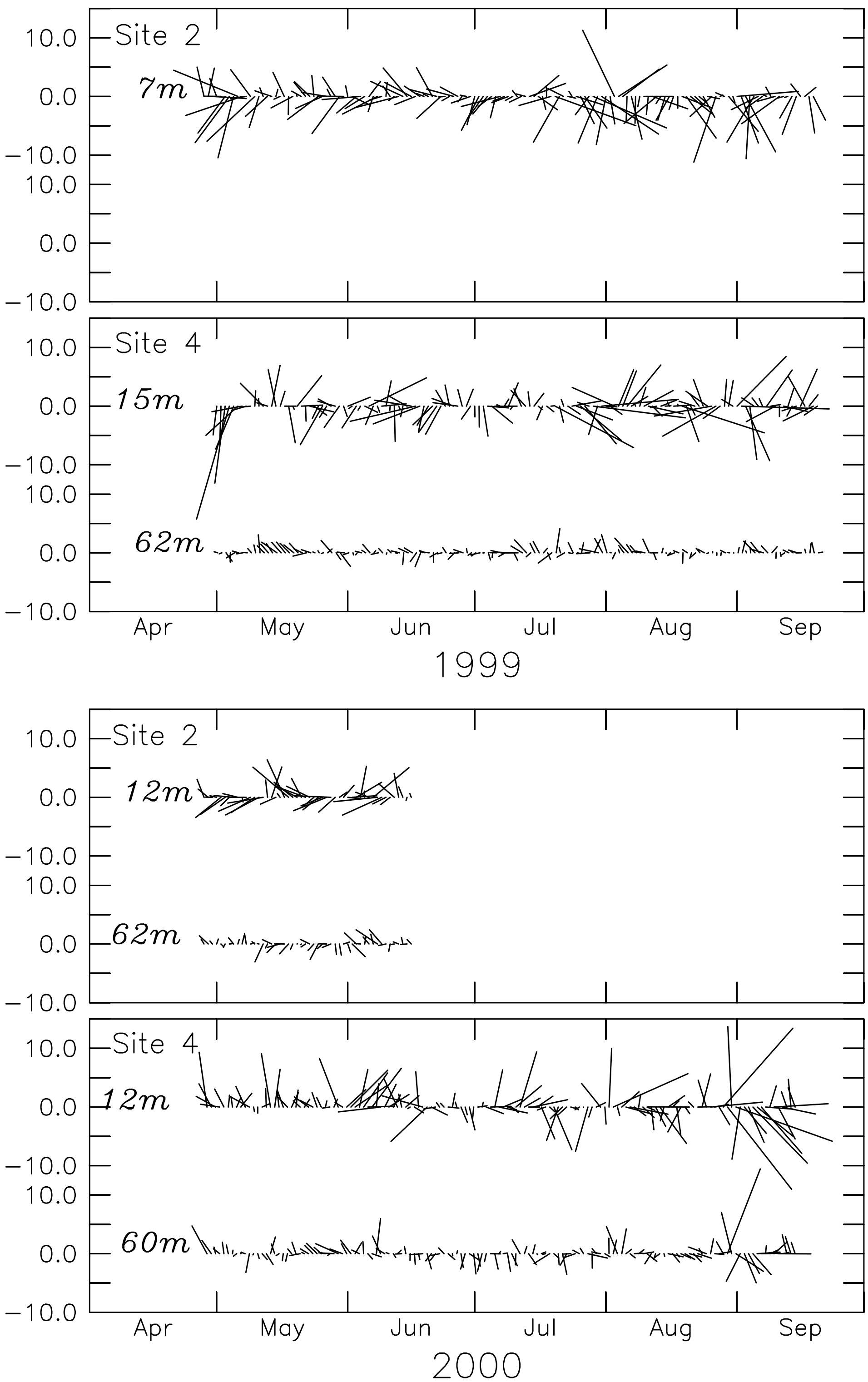


Stabeno: 70-m isobath -- Fig. 10



Stabeno: 70-m isobath -- Fig. 11